I discuss the simultaneous effects of Zeeman and spin-orbit fields during the evolution from BCS to BEC superfluidity for ultra-cold fermions. I focus on spin-orbit couplings with equal Rashba and Dresselhaus strengths, and show that topological phase transitions of the Lifshitz class occur through the emergence of Majorana and/or Dirac fermions as Zeeman and spin-orbit fields are varied. Topological quantum phase transitions in superfluids with non-s-wave order parameters have been conjectured theoretically for p-wave and d-wave systems for many years, but never observed experimentally due to the absence of tunable parameters. However, Zeeman or spin-orbit fields and interactions can be tuned in the context of ultra-cold atoms and allow for the visitation of several different phases. For systems with zero Zeeman field, the evolution from BCS to BEC superfluidity in the presence of spin-orbit effects is only a crossover as the system remains fully gapped, even though a triplet component of the order parameter emerges. In contrast, for finite Zeeman fields, spin-orbit coupling induces a triplet component in the order parameter that produces nodes in the quasiparticle excitation spectrum leading to bulk topological phase transitions of the Lifshitz type. Additionally, a fully gapped phase exists, where a crossover from indirect to direct gap occurs. For spin-orbit couplings with equal Rashba and Dresselhaus strengths the nodal quasi-particles are Dirac fermions that live at and in the vicinity of rings of nodes. Transitions from and to nodal phases can occur via the emergence of zero-mode Majorana fermions at phase boundaries, where rings of nodes of Dirac fermions annihilate. Lastly, I characterize different phases via spectroscopic and thermodynamic properties and conclude that Lifshitz is the “Lord of the Rings”.
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